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Impact of a minority relativistic electron tail interacting with a thermal plasma containing high-atomic-number impurities

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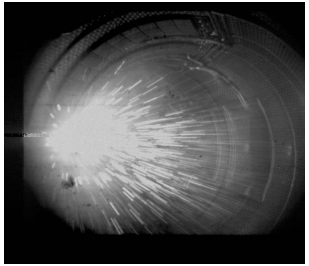
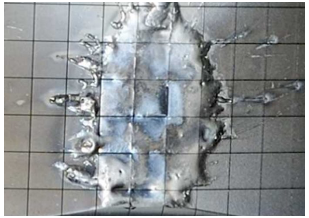
Motivation: Tokamak disruptions

- Current ITER strategy: inject high Z impurities to terminate (Ne, Ar)
  - Dissipate magnetic energy via radiation
  - Regulate plasma current
  - *But how does a plasma with runaway electrons interact with these impurities?*



RE impacting carbon tiles on Tore Supra (Source: CEA-IRFM)



Cooled molten Be tiles in JET (Source: EURO*fusion*)

Ionization balance/charge state population?

Radiation?

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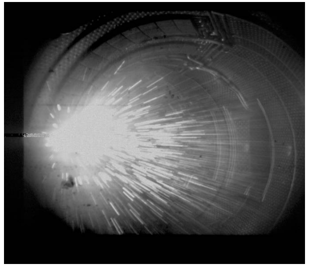

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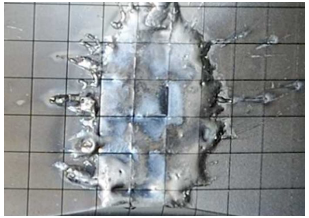


Cooled molten Be tiles in JET (Source: EURO*fusion*)

Ionization balance/charge state population?

Radiation? → Collisional-Radiative modeling

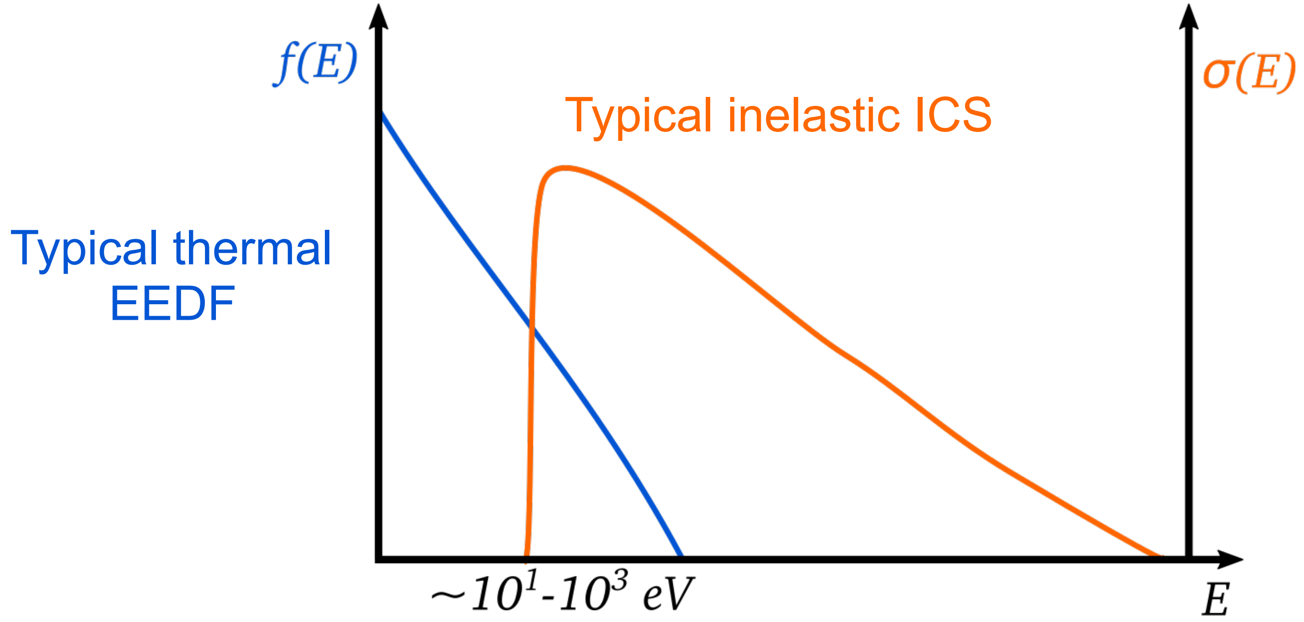
CR models in the fusion community

- US groups have long used KPRAD to couple with plasma codes and probe experiments on DIII-D, C-MOD [Whyte *et al.* Proceedings of the 24th European Conference on Controlled Fusion and Plasma Physics 21A:1137 (1997)]
- EU groups have used ADAS at a mature level [Summers *et al.* AIP Conference Proceedings 901, no. 1 (2007)]
- HEDP often uses FLYCHK [Chung *et al.* HEDP 1 3 (2005)]

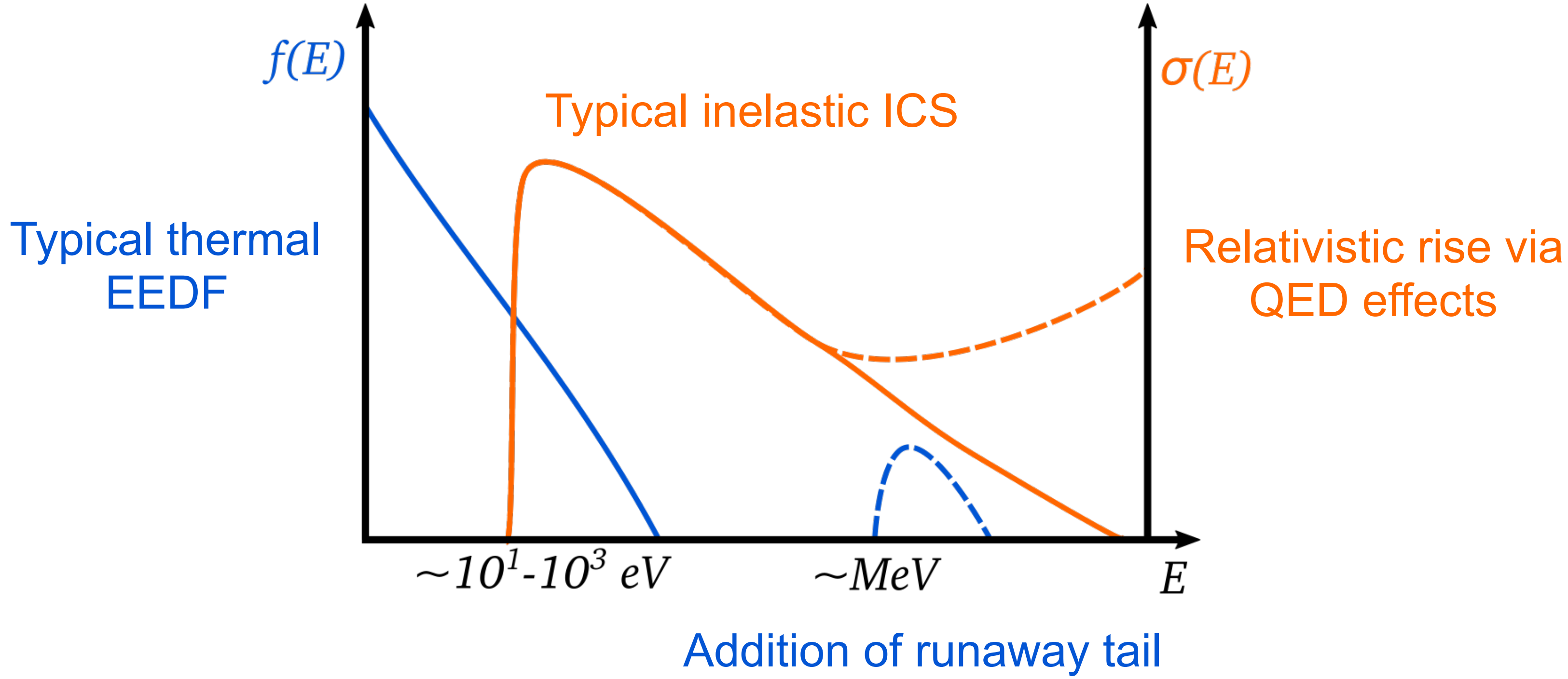
General idea of this work:

Do we need to do anything different from standard modeling to describe impact of runaways, and does it make a difference?

Interaction of EEDF with inelastic cross-sections



Interaction of EEDF with inelastic cross-sections



Our approach

- Developing fork of FLYCHK [Chung *et al.* HEDP 1 3 (2005)], flychklite, to allow relativistic corrections & arbitrary EEDF
- QED effects manifest at relativistic e^- energies, generalized Breit interaction [Fontes *et al.* PRA **47** 2 (1993)]
    - Higher order correction to Coulomb interaction
    - Generally employed for binding energy, but not always cross-sections
- Enhanced e^--e^- coupling increases cross-section

Required input data: relativistic ICS

- We modify base inelastic ICS in FLYCHK to transition to a relativistic approximate ICS

$$\sigma_{i\to j}^{\mathrm{TOT}} = (1 - S(E))\sigma_{i\to j}^{\mathrm{NR}} + S(E)\sigma_{i\to j}^{\mathrm{R}}$$

- Simulate relativistic effect via Møller-Bethe-like analytic relativistic-rise

$$\sigma_I^{rel} \sim \left(\log\left(\frac{\beta^2}{1-\beta^2}\frac{0.5 m_e c^2}{\Delta I_Z^i}\right) - \beta^2\right)$$

$$\beta = v/c$$

$$\frac{dn_i}{dt} = -n_i \sum_{j\neq i}^{N_L} W_{ij} + \sum_{j\neq i}^{N_L} n_j W_{ji} \qquad 1 \leq i \leq N_L$$

<u>Model assumptions:</u>

In this work solving, SS problem

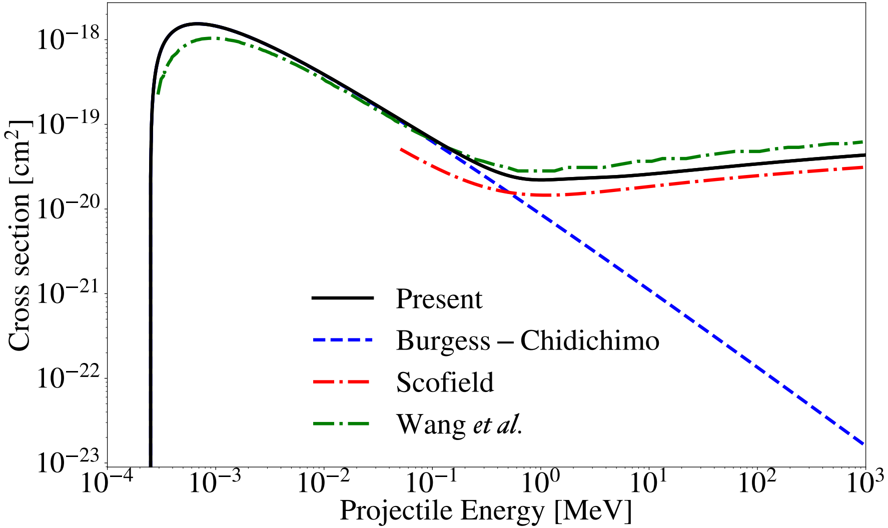
Optically thin

No IPD

Simulate relativistic effect via Møller-Bethe-like analytic form

- Møller-Bethe-like form not a new thing
- Back to 1930s
  - Moller *Annalen der Physik* 406 5 (1932)
  - Bethe *Z. Physik* 76 5 (1932)
- Provides a general prescription we can apply to any inelastic collision
  - But we try to benchmark against QM calculations

Ar L-shell ionization ICS

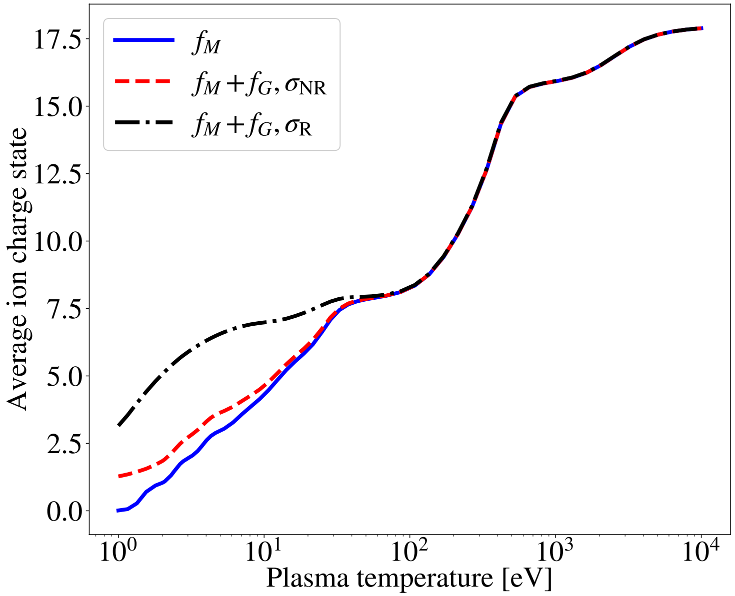


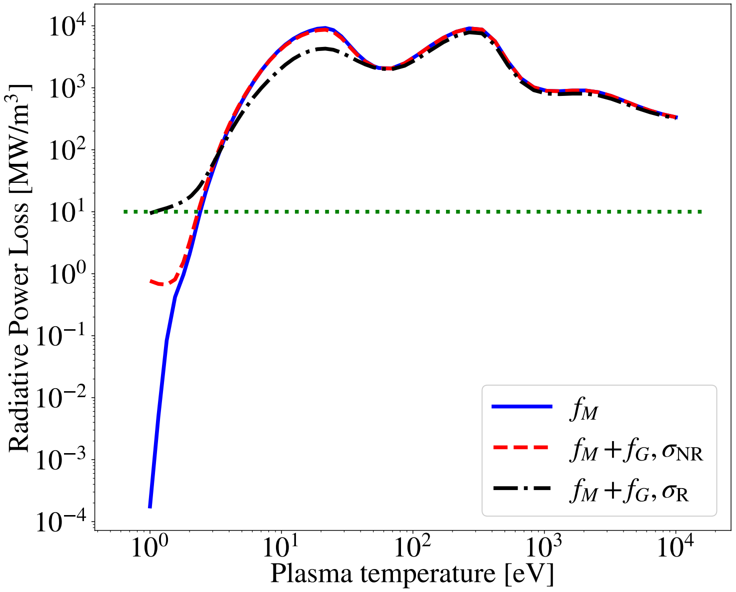
FLYCHK/Burgess & Chidichimo MNRAS 203 1269 (1983)
Scofield PRA 18 963 (1978)
Wang *et al.* JPB 51 145201 (2018)

What effect does this have?

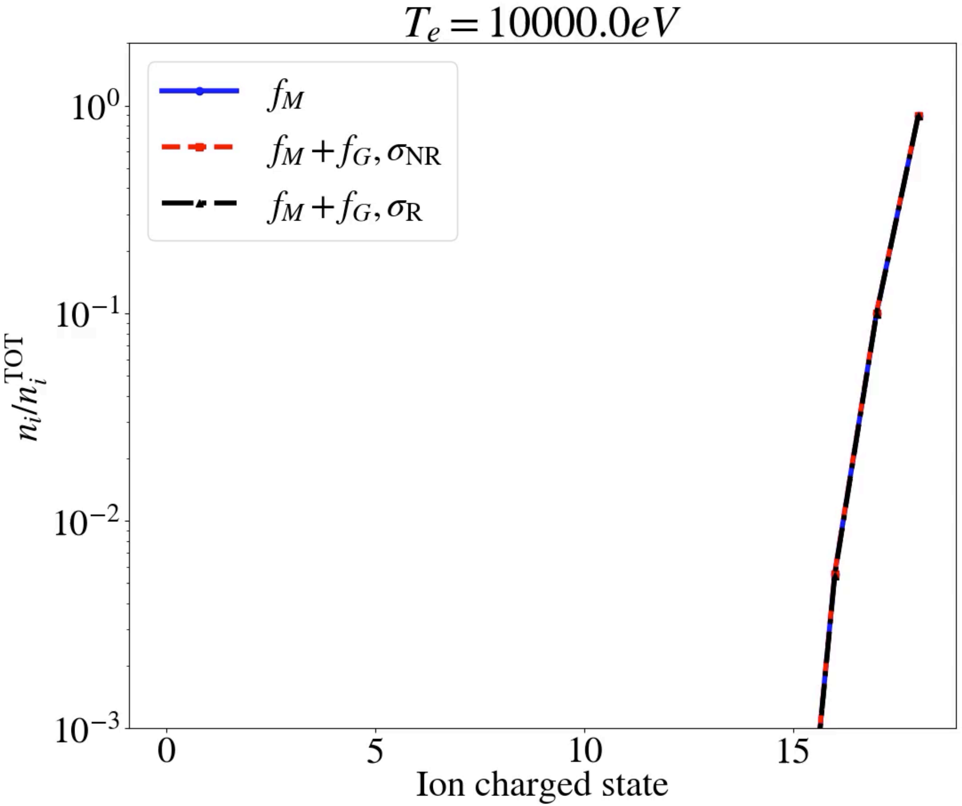
D+Ar plasma with 10 MeV Gaussian tail

$n_D = n_{Ar} = 10^{14}$ cm^{-3} ; Runaway fraction ~10^{10}-10^{11} cm^{-3}
carrying an ITER-like current (~10 MA)





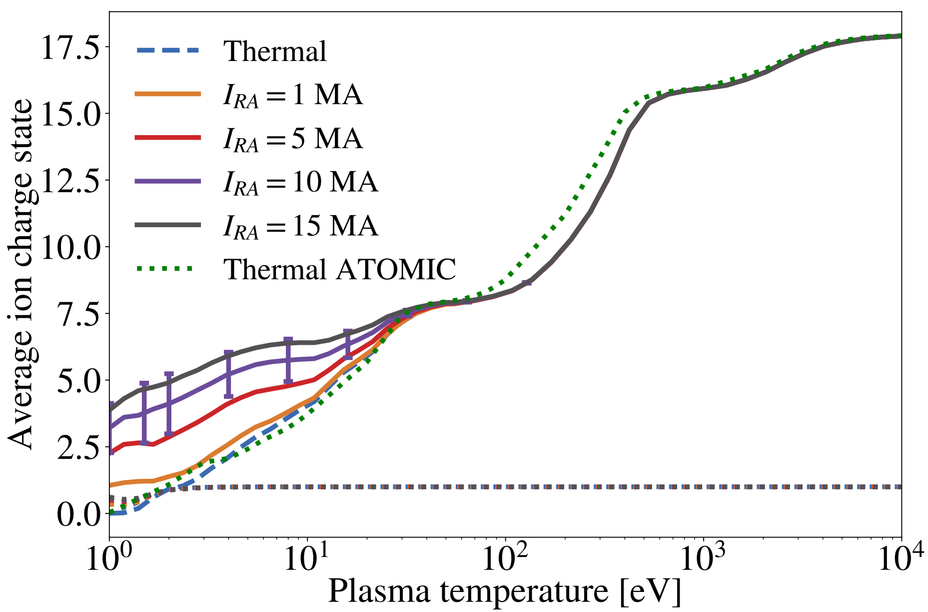
Ar CSD spread with cooling T_e

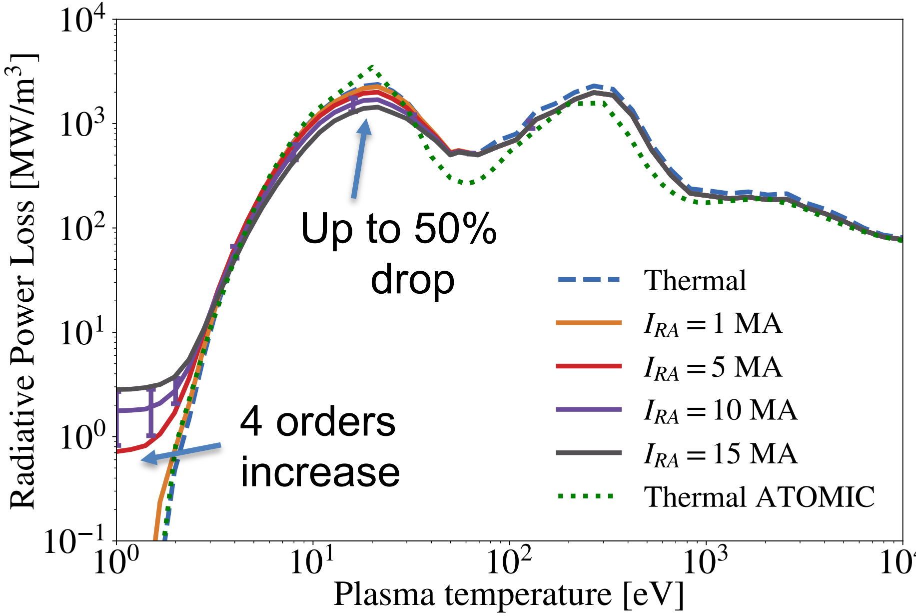


- CSD spread as plasma cools is crucial to e⁻ scattering
- Runaway tail yields greater mean charge, over a wide range of charged states

D+Ar plasma with ITER-like currents

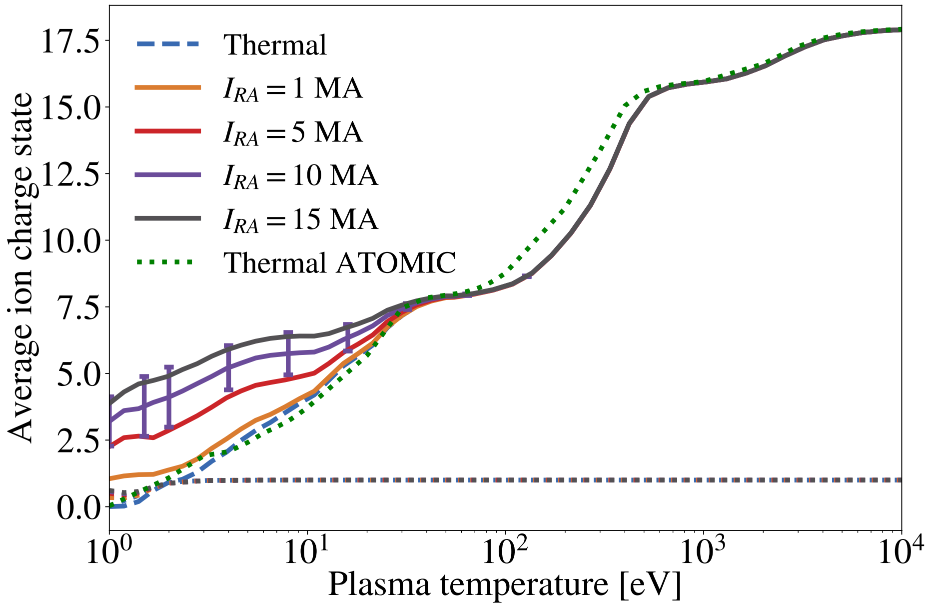
$n_D = n_{Ar} = 10^{14}$ cm^{-3} ; Runaway fraction set to carry current ~10^{10}-10^{11} cm^{-3} .





ATOMIC - LANL CR model [Fontes *et al.* JPB 48 144014 (2015)]

Is this effect real? UQ can help

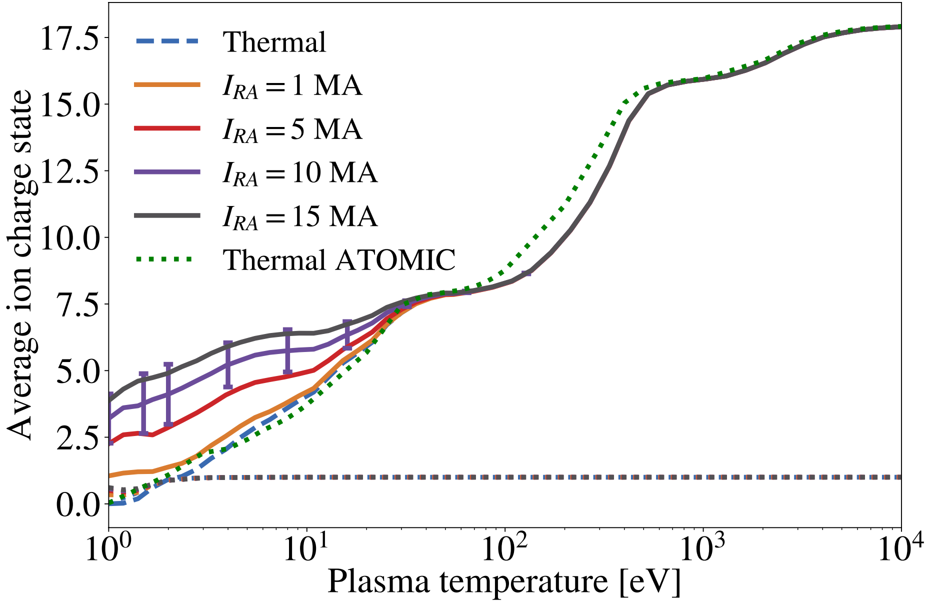


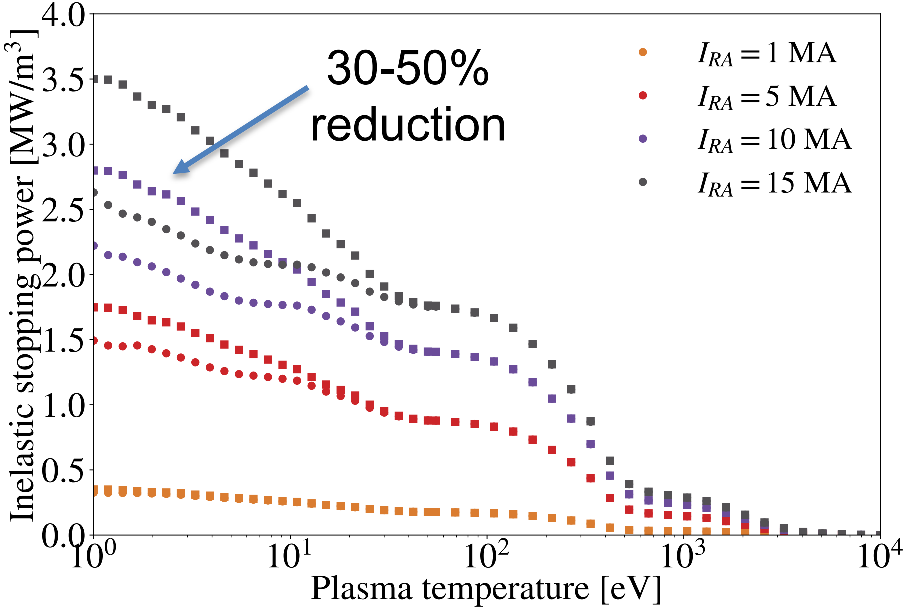
Ranges computed from epistemic UQ study with Dakota software [https://dakota.sandia.gov/]

Vary relativistic rise of σ_{ion} and σ_{exc} with prefactors between 0.5 and 2, to account for variation in approximate formula

500 samples over parameter space with Latin Hypercube Sampling.

CSD effect on Bethe stopping power





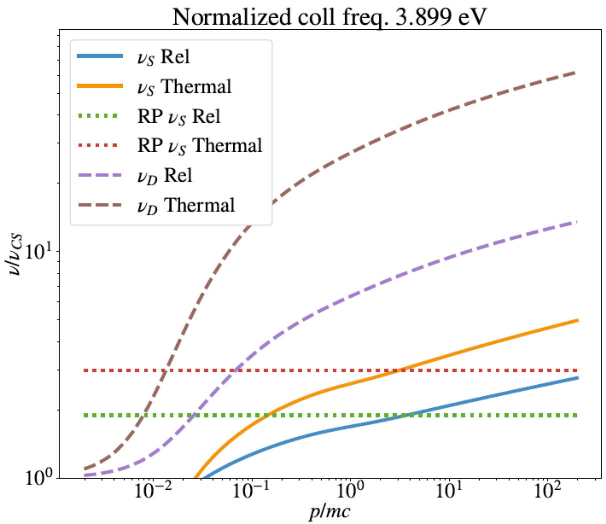
BSP: $$-\frac{dE}{dx} = \sum_{\alpha} \frac{e^2}{\epsilon_0 m_e c^2} \frac{n_{e\alpha}}{\beta^2} \left[\ln\left(\frac{2 m_e c^2 \beta^2}{\langle I_\alpha \rangle (1-\beta^2)} \right) - \beta^2 \right]$$

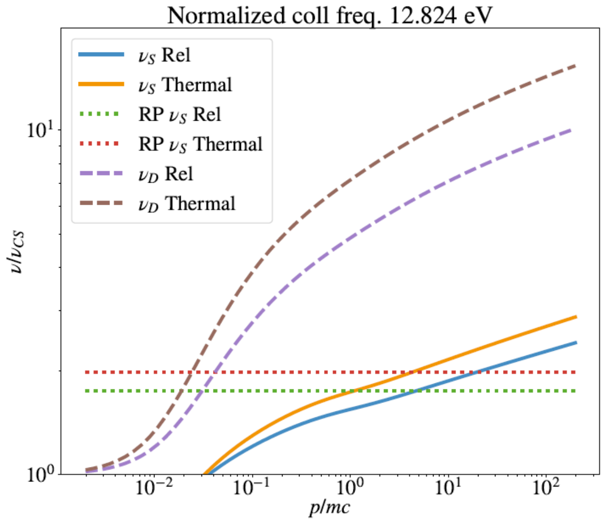
■ Thermal CSD

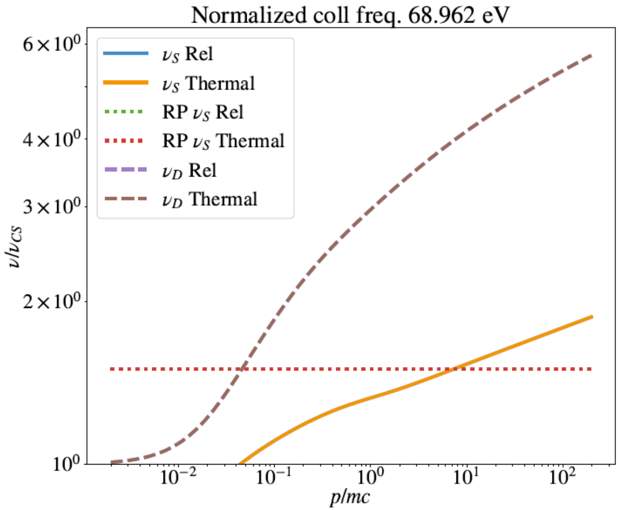
● RA enhanced CSD

CSD effect on friction & deflection collision frequencies

Using formulae presented in Hesslow *et al.* PRL118 25 (2017)
Compared with Rosenbluth & Putvinski, NF 37, 1355 (1997)







$$\nu_S^{ee} = \nu_{S,\mathrm{cs}}^{ee}\left[1 + \sum_j \frac{n_j N_{e,j}}{n_e \ln\Lambda}\left(\frac{1}{k}\ln\left(1 + h_j^k\right) - \beta^2\right)\right] \quad \nu_D^{ei} = \nu_{D,\mathrm{cs}}^{ei}\left(1 + \frac{1}{Z_{\mathrm{eff}}}\sum_j \frac{n_j}{n_e}\frac{g_j(p)}{\ln\Lambda}\right)$$

Summary

- Including enhanced relativistic ICS → potential for enhanced <Z> and RPL at lower T_e when minority RE are present
    - These low T_e are crucial for cooled, post-disruption discharges

- We must continue exploring
    - RE energies, profiles, densities
    - Current machines as well as ITER
    - Improving atomic physics input data

Where to from here?

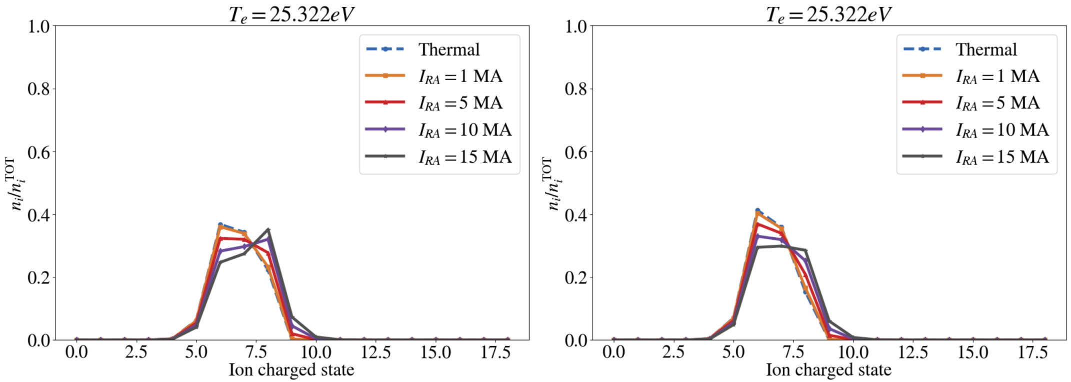
- Time-dependent cooling history
  - Rapid timescales in disruptions, how bad are steady-state data approximations?

- Couple CR into plasma codes for consistent evolution of runaway EEDF, T_e, impurity ions
  - Continuum RFP model
  - 6D particle code (Chris McDevitt)

- Experimental verification
  - Discussing with tokamak operators
  - Controlled lab experiment

Where to from here?

- Further understand impact of RE and relativistic ICS to discharge composition
  - unique spectra produced by runaways
  - Joint effort of simpler flychklite CR with detailed LANL ATOMIC code
  - Impact of excitations



(Left) Charge state with excitations, and (Right) without excitations (coronal assumption)